

# DEFLECTION AND FRAGMENTATION OF NEAR-EARTH ASTEROIDS

Thomas J. Ahrens, Lindhurst Laboratory of Experimental Geophysics, Seismological Laboratory 252-21, California Institute of Technology, Pasadena, CA 91125; Alan W. Harris, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, California, CA 91109

## **ABSTRACT**

Collisions by near-earth asteroids or the nuclei of comets pose varying levels of threat to man. A relatively small object, ~100 m diameter, which might be found on an impact trajectory with a populated region of the Earth, could potentially be diverted with a velocity of ~1 cm/sec from an Earth impacting trajectory by impact (at 12 km/sec) by a rocket launched,  $10^2$  to  $10^3$  Kg impactor. For larger bodies, the use of kinetic energy impactors appear impractical because of the larger mass requirement. For any size object, nuclear explosions appear to be more efficient, using either the prompt blow-off from neutron radiation, the impulse from ejecta of a near-surface explosion for deflection, or, least efficiently, as a fragmenting charge.

## 1. INTRODUCTION

Several hundred asteroids and comet nuclei with diameters  $> 10^2$  m, in Earth crossing orbits, have been discovered. Upon extrapolating this known population of near Earth objects (NEO's) to those not yet discovered, it is estimated that  $\sim 2 \times 10^3$  objects  $\geq 1$  km in diameter are present in a transient population. The largest earth crossing asteroids have diameters in the  $\sim 10$  km range. It is unlikely that any still larger objects remain undiscovered, however, it is likely that additional objects as large as 3-5 km in diameter may remain undiscovered.

Scientific interest in NEO's is great because it appears that many of these objects are main belt asteroids which have been perturbed into terrestrial planet crossing orbits, and thus give rise to a large fraction of impactor flux on terrestrial planet surfaces<sup>1</sup>. Objects as small as 5-10 m in diameter, can be telescopically observed. Recently 1991 BA, in the 5-10 m size was detected. This object passed within  $\sim 10^5$  km of the earth<sup>2</sup>. Small objects with diameters  $> 0.6$  and  $0.2$  m for stony and iron objects are believed to be representative of the terrestrial meteorite collection. Since the number distribution of different meteorite classes correlates poorly with asteroid type as inferred from reflectance spectra of main belt asteroids, it may be that the present terrestrial meteorite collection is a poor sample of the asteroid population. To further study asteroids, one or more unmanned flyby or rendezvous missions to near earth asteroids (NEA's) are currently being planned by NASA<sup>3</sup>. Moreover, the composition of NEA's is of great interest since these represent possible minable resources which, in principle, could supply raw materials, including water, and hence, oxygen and hydrogen for extended space flights in the future.

New comets are brought into the swarm of NEO's by gravitational perturbation from their orbits in the Kuiper belt and/or Oort cloud<sup>4</sup>. Some objects currently classed as near-earth asteroids may be devolatilized comets.

Planet crossing objects are removed from the population either via collision with a planet or by gravitational perturbation which causes them to be ejected into hyperbolic

orbits.

Although earth-crossing asteroids have been recognized telescopically since 1932, when Karl Reinmuth discovered 1862 Apollo, it was the American geologist, G. K. Gilbert whose work on Meteor Crater, Arizona, and many later workers, made it apparent that the impact of earth-crossing asteroids and comets produce the ~120 known meteorite impact craters on the earth and virtually all the craters on the moon.

The concept that the impact of any asteroid or comet with the earth could, in principle, have a catastrophic effect on life on the earth logically followed from the 1980 discovery of Alvarez et al.<sup>5</sup> of the worldwide platinum group element-rich impact ejecta dust layer at the Cretaceous-Tertiary (K-T) boundary. The gradual great acceptance of the Alvarez hypothesis that the impact of ~10 km or larger bolide with the earth at the K-T boundary (65 Ma ago) gave rise to a great extinction of more than 50% of the known genera and probably 90% of all species, recently motivated several technical meetings, focussed on this topic, in several countries. Sparked by public concern, the United States House of Representatives in 1991 requested that the National Aeronautics and Space Administration to conduct a (workshop) series of studies of the asteroid-impact threat to the earth <sup>6</sup>, and the means to prevent it <sup>7</sup>. The recent Near-Earth Object Detection Workshop <sup>6</sup>, quantified the hazards to populations of different size earth impactors based, in part, on the results of an earlier, 1981, workshop <sup>8</sup>. Using the estimated population of NEO's and their size distribution, objects with diameters of about 10 m impact the earth almost annually, and although visible and audible for distances of  $10^2$  to  $10^3$  km, these objects largely break up and expend their typically 10 kton (of TNT) energy in the atmosphere. Objects of about 100 m diameter include the 1908 Tunguska event (~10 Mton) energy. This size impactor has a frequency of about once every ~300 years. The Tunguska bolide did not hit the earth's surface and yet did great damage. These objects, although inducing local areas of devastation of  $\sim 5 \times 10^3$  km<sup>2</sup>, have an annual probability of leading to the deaths of a given individual of only  $3 \times 10^{-8}$ /year. Although less frequent, once every 0.5

Ma, earth impactors of the ~2 km diameter size are inferred to be the minimum size which can produce global catastrophic effects (25% human mortality). Thus the annual individual death probability from such an event is of the order of  $5 \times 10^{-7}$ , which is comparable to the annual worldwide probability of an individual succumbing in a commercial airplane accident. When viewed in this way, it appears to us that for society to deal with this problem rationally, it ought to expend not more than perhaps a fraction of the amount committed to air safety and control. We believe this would be in the range of  $10^7$  to  $10^8$  dollars per annum worldwide. As was concluded by the Near Earth Object Detection Workshop, funding at this level would vastly improve our knowledge of the population and distribution of near earth objects using ground-based and possibly space-borne telescopes. The technologies which might be employed to divert asteroids can be expected to change so rapidly that it appears premature to conduct detailed engineering studies or build prototypes.

To quantify the present work especially with regard to nuclear explosive cratering in the low gravity asteroid environment, we employ recent studies of cratering at varying gravities and atmospheric pressures <sup>9</sup> and impact ejecta scaling <sup>10</sup>, which were not available to earlier studies <sup>11, 12</sup>.

In the present paper we examine the orbit perturbation requirements to deflect objects from the Earth, which upon astronomical orbit determination are found to have earth impacting trajectories. We then examine several physical means for both deflecting and explosively fragmenting such objects. We consider NEO's in three size ranges, 0.1, 1, and 10 km in diameter. Their fluxes, on the total area of the earth per year are respectively,  $10^{-3}$ ,  $10^{-5}$ , and  $10^{-8}$ . It is unlikely that any undiscovered objects > 5 km exist. Significantly smaller objects pose very little threat, because they do not penetrate the atmosphere intact. Short duration responses, which might be considered for new comets, have recently been described by Solem <sup>12, 13</sup>. This study addresses the physical means of encountering NEO's with spacecraft-bearing energetic devices many years, or even

decades, before projected earth impact.

## 2. NEAR EARTH ASTEROID ORBIT DEFLECTION CONSIDERATIONS

Two possible approaches to orbit deflection are perturbation perpendicular to orbital motion and perturbation along the trajectory of motion, e.g. either speeding up or slowing down the orbital velocity relative to the Sun.

An increment of velocity,  $\Delta v$  applied transversely to a circularly orbiting particle induces an eccentricity or inclination which results in an oscillation about the original orbiting point of amplitude.

$$\delta \sim \frac{\Delta v}{v_0} a \quad (1)$$

where  $v_0$  is the orbit velocity (30 km/s for the Earth) and  $a$  is the semimajor axis. Thus to perturb a particle by  $\delta \sim 1 R_\oplus$ . The  $\Delta v$  required is

$$\Delta v \sim \frac{v_0 R_\oplus}{a} \approx 1 \text{ m/s} \quad (2)$$

To perturb a body on a time  $t$  short compared to the orbit period, a simple linear estimate suffices:

$$\delta = \Delta v t \quad (3)$$

To perturb a body  $1 R_\oplus$  in time,  $t$ , requires

$$\Delta v \sim \frac{R_\oplus}{t} \sim \frac{75 \text{ m/s}}{t, \text{ days}} \quad (4)$$

Note that the linear estimate reduces to the orbital oscillation after  $\sim 1$  radian of orbital motion.

In contrast, an increment of velocity  $\Delta v$  applied parallel to the orbit motion changes the orbital semimajor axis, but more importantly, changes the orbit period which results in a secular drift of the perturbed body from its original path. For an initially circular orbit, the mean drift velocity,  $\Delta v'$  is in the opposite sense and larger than  $\Delta v$ :

$$\Delta v' = -3\Delta v \quad (5)$$

An even larger amplification occurs if the impulse is applied at the perihelion of an eccentric orbit. For an eccentricity of 0.5,  $\Delta v' \approx -5\Delta v$ . Thus, over a time long compared to the orbit period, an increment  $\Delta v$  applied parallel to  $v$  produces a deflection of

$$\delta \sim 3\Delta v t \quad (6)$$

Hence, for 1  $R_{\oplus}$  deflection

$$\Delta v \sim \frac{R_{\oplus}}{3t} \sim \frac{0.07 \text{ m/s}}{t, \text{ years}} \quad (7)$$

Thus, with a lead time of the order of a decade, a velocity increment as small as  $\sim 0.01$  m/sec could suffice to divert an asteroid from a collision course with the Earth.

### 3. IMPLEMENTATION OF ORBITAL DIVERSION

Several scenarios are considered, including deflection via kinetic energy impactor, mass driver systems, as well as nuclear explosive radiation and blow-off, and ejecta impulse from cratering explosions.

#### A. DIRECT IMPACT DEFLECTION

It is feasible to deflect a small ( $\sim 10^2$  m diameter) asteroid via direct impact because:

(1) The kinetic energy delivered for even a modest encounter velocity ( $\sim 12$  km/sec) of an upper stage launched spacecraft is much more efficiently coupled (70 to 80%) to the asteroid<sup>14</sup> than surface explosions. The energy density at 12 km/sec is  $70 \times 10^{10}$  ergs per g of impactor. This is much greater than typical chemical explosive energies ( $4 \times 10^{10}$  ergs/g), and as demonstrated below the ejecta throw-off from such an impact will suitably perturb the NEO.

(2) The cratering efficiency on a small (100 m diameter) asteroid (escape velocity 5 cm/sec) is unmeasured. However, extrapolating small scale studies (at high and low gravities) it is expected to be  $\sim 10^4$  times<sup>10, 15</sup> the earthly value of 2.8 tons of rock per ton

of equivalent explosive yield <sup>16</sup>. For example, we calculate the impact of a 200 kg projectile onto 100 m diameter,  $10^6$  ton,  $2 \text{ g/cm}^3$  asteroid, induces a gravity limited crater with  $10^5$  tons of ejecta having greater than escape velocity. This will perturb the velocity object  $\sim 0.6 \text{ cm/sec}$  even if a (30 bar) strength controlled crater formation is assumed <sup>17</sup> and  $\sim 10^2$  tons per equivalent ton of explosive is calculated.

It is possible that for small asteroids, an impactor device, e.g., the U.S. Space Defense Initiative's technology derived from the Boeing Company's Lightweight Exoatmospheric Projectile, could be utilized.

At larger asteroid diameters of 1 km, the increase in asteroid mass by a factor of  $10^3$  reduces the resulting perturbation velocity by the same factor. Moreover, the cratering efficiency declines on account of the increased gravity of the asteroid and thus direct impact deflection in this size range becomes impractical.



## B. MASS DRIVERS FOR DEFLECTION

As a long-term response, one might imagine employing a mass driver system which is in operation for many years. A lead time of three decades, prior to earth encounter would, from Eq. 7, require a  $\Delta v \sim 0.2$  cm/s. It might be technically feasible to deliver a reaction engine or "mass driver" to an asteroid which will launch ejecta mined from part of the asteroid. Such a device operating on a small asteroid over a decade time-scale, provides the needed  $\Delta v$ . For an ejection velocity of  $\sim 0.3$  km/sec, the ejected mass necessary to produce a recoil of 0.2 cm/sec is

$$\Delta m \sim \frac{0.2 \text{ cm / sec}}{0.3 \text{ km / sec}} m_a \sim 7000 \text{ tons}$$

where  $m_a$  is the asteroid mass. Although such a system might be technically feasible, it will become clear from what follows that nuclear energy offers a much less expensive solution.

## C. NUCLEAR EXPLOSION RADIATION DEFLECTION

By detonating a nuclear explosive which emits a large portion of its yield via neutrons, a large area of the asteroid/comet surface can be irradiated<sup>18</sup>. Subsequent blow-off of surface material in excess of the escape velocity can provide the necessary impulse for orbital deflection as sketched in Fig.1. We have found that by detonating a charge at a normalized altitude  $h/R = \sqrt{2}-1 \cong 0.4$ , where  $h$  and  $R$  are the altitude of the charge above the asteroid surface and  $R$  is the radius of the asteroid, a maximum dose of  $f_{\max} = 0.27$  times the total radiative yield is delivered to 0.296 times the unit area of an assumed spherical asteroid. For a mean neutron cross-section of  $10^{-24}$  cm<sup>2</sup>, an assumed asteroid density of 2 g/cm<sup>3</sup> and mean atomic weight of 25, a characteristic neutron penetration depth of  $\sim 20$  cm is inferred. Thus an asteroid volume corresponding to a 20 cm deep surface shell covering 0.296 of the surface area is irradiated, which for a 50 m radius object with a density of

2g/cm<sup>3</sup> will have an irradiated shell of mass 3.7 x 10<sup>9</sup> g. We further assume that the fraction, e=0.3, of the explosive yield is delivered as neutron or other radiation and this radiation is completely converted to internal energy, ΔE, per unit mass in the irradiated shell. The energy per unit kiloton of explosive yield delivered to the irradiated shell is thus

$$\Delta E = f_{\max} e (4 \times 10^{19}) \text{ ergs} \quad (8)$$

where 4 x 10<sup>19</sup> is the equivalent number of ergs in a kiloton of explosive yield. This heating at constant volume of the shell will result in an increase in the pressure (per kiloton), ΔP of

$$\Delta P = \gamma \rho \Delta E \quad (9)$$

where γ is the thermodynamic Gruneisen ratio. We assume γ to be unity, and ρ is the asteroid/comet density which we assume is 2 g/cm<sup>3</sup>. This irradiation occurs in less than the ~10<sup>2</sup> μs required for the sonic wave travel time through the shell. From Eq. 9, this energy density will raise the shell thermodynamic pressure to ~1.7 kbar (per kiloton). As depicted in Fig. 1, this pressure increase accelerates the irradiated shell to the right, and a stress wave pulse is propagated to the left within the asteroid. The right moving irradiated shell and left propagating stress wave causes the irradiated shell to break away from the asteroid (to conserve momentum) as depicted in Fig. 1. The stress wave propagating to the left in the asteroid appears to be sufficiently low amplitude such that little further destruction of the object is expected to occur. By assuming a compressional wave velocity, C<sub>p</sub>, of 2 km/sec, we find

$$\Delta v_r = \Delta P / \rho C_p \quad (10)$$

in the asteroid material, the resulting outward particle velocity of the shell material is 44 m/sec/Kton. Considering only the component of velocity along the direction between the explosive and the asteroidal center yields a reduced velocity of ~31 m/sec/Kton. For the 50 m radius asteroid, this velocity is much greater than the escape velocity of 5.3 cm/sec. By conservation of momentum, the rebounding surface material translates into an asteroidal perturbation velocity of 11 cm/sec/Kton. For 1 and 10 km diameter objects, the

comparable rebound velocities are  $11 \times 10^{-3}$  and  $11 \times 10^{-6}$  cm/sec/Kton. However, if  $e = 0.03$  rather than 0.3, these velocities will decrease by a factor of 10. Thus we conclude that to achieve deflection velocities on the order of 1 cm/sec requires detonation of 0.01 to 0.1 Kton, 0.01 to 0.1 Mton, and 0.01 to 0.1 Gton nuclear explosives, for asteroids of diameter 100 m, 1 km, and 10 km, respectively.

#### D. DEFLECTION BY SURFACE NUCLEAR EXPLOSIVE

Another approach to the use of nuclear explosives employs the use of a surface charge to induce cratering on the asteroid. The thrown-off ejecta effectively induces a velocity change in the asteroid and the ejecta is highly dispersed and is not expected to be a hazard when it is encountered by the Earth. This method suffers the disadvantage in that the asteroid may be inadvertently broken into large fragments which may represent a hazard to the Earth. For 0.1, 1, and 10 km diameter, we examine the nuclear explosive surface charge required to perturb asteroid velocity in the case that gravity limits ejecta production, and the asteroid is weak. For the case of a 0.1 km asteroid, it is conceivable that cratering processes are limited by asteroid yield strength. We examine this case, also. The mass of ejecta cratered per unit mass of explosive, when cratering is limited by gravity, is given by Housen et al.<sup>10</sup>

$$\pi_v = \{0.16 - 0.24 (d/a) \pi_2^{0.194} + 2.11 [(d/a) \pi_2^{0.194}]^2 - 2.38 [(d/a) \pi_2^{0.194}]^3 + 0.663 [(d/a) \pi_2^{0.194}]^3\} / [\pi_2^{0.581}] \quad (11)$$

Eq. 11 was obtained on the basis of small-scale laboratory centrifuge experiments under high gravity, reduced pressure, and large-scale nuclear explosive tests. Equation 11 also describes a limited number of small scale experiments conducted by Johnson et al.<sup>19</sup> at reduced gravity and reduced atmospheric pressures. Here  $\pi_v$  is the mass of material ejected from the crater per unit mass of explosive. It is assumed that nuclear explosives can be assigned an equivalent TNT (high explosive) mass based on their yield. Here  $d$  and “ $a$ ” are explosive depth and equivalent explosive mass radius. Also,  $\pi_2$  is defined as the gravity

scaling parameter

$$\pi_2 = (m/\delta)^{1/3} g/Q \quad (12)$$

where  $m$  is the equivalent charge mass and  $\delta$  is charge density. For simplicity, we again assume that charge density and asteroid density are equal at a value of  $2 \text{ Mg/m}^3$ .  $Q$  is the energy per unit mass of TNT which is  $4 \times 10^6 \text{ J/kg}$  and  $g$  is asteroid surface gravity. Since the only ejecta which will alter the orbit of an asteroid must be thrown off the object at a velocity exceeding the escape velocity, we use the generalized equations of Housen et al.<sup>10</sup> to calculate the mass of ejecta,  $m_e$  launched at speeds greater than escape velocity

$$m_e/(\rho R_c^3) = 0.32 [2R/R_c]^{-0.61} \quad (13)$$

where  $R_c$  is the final crater radius. The mass of ejecta escaping the asteroid and the resulting asteroid velocity perturbation versus surface explosive charge are shown in Fig.

2. To relate  $R_c$  to  $m_e$ , we assume a conical-shaped crater with a depth to diameter ratio of 5. Thus far for surface explosions  $\sim 0.1$ ,  $10^2$  and  $10^4 \text{ Kton}$  of explosive energy, detonated at the asteroid surface, are required to perturb 0.1, 1, and 10 km diameter asteroidal or cometary object's orbital velocity by  $\sim 1 \text{ cm/sec}$ . Moreover, for a 100 m asteroid strength scaling<sup>17</sup> may apply. In the case of an effective yield strength of 30 bars, Fig. 2 indicates only 500 kg would be required to perturb a small asteroid by  $1 \text{ cm/sec}$ .

Thus at best, surface explosions are no better than radiative stand-off explosions, and the requirements are subject to greater uncertainty.

## 5. FRAGMENTATION AND DISPERSAL

Small scale fragmentation experiments on solid rocks demonstrate that the bulk of the fragments of a collisional disruption have velocities of  $\sim 10 \text{ m/s}$ . However, the "core" or largest fragment has been demonstrated to have a differential velocity of no more than  $\sim 1 \text{ m/s}$  (e.g. Nakamura and Fujiwara<sup>20</sup>). From equation 4, if the body is fragmented  $\sim 75$  days before earth encounter then most of the  $\geq 10 \text{ m}$  fragment will still impact the Earth.

For a small object (0.1 to 1 km) dispersal of the bulk of the fragments into the Earth's

atmosphere may be sufficient, as long as no fragments  $\geq 10$  m are allowed. For a really large object ( $> 1$  km) fragmentation would need to be conducted one or more orbits before intersection with the Earth to assure that most fragments miss the Earth. In general, the debris cloud would spread along the orbit according to Eq. 7 and in the transverse direction according to Eq. 2. For a characteristic velocity of ejecta of 10 m/s, the debris cloud would be  $\sim 10R_{\oplus}$  in radius (with some oscillation about the orbit) and grow in length by  $\sim 200 R_{\oplus}$  per orbit period. Thus, if the asteroid were destroyed one orbit before encounter, the Earth might encounter as little as 0.1% of the debris. But more conservatively, if many large fragments with  $\Delta v \leq 1$  m/s remained, as much as 10% of that mass might be intercepted. Thus fragmentation is likely to be a safe choice only for long lead-time response (decades) or for relatively small bodies where the fragments may still hit the Earth.

"Catastrophic disruption" is generally defined as fragmentation where the largest fragment is  $\leq 1/2$  the total mass. The energy density to accomplish this decreases with increasing size of body, and becomes rather uncertain when extrapolated to 1-10 km size bodies (e.g. Housen & Holsapple<sup>21</sup>). However, for the present purpose, we are interested in the energy density necessary to break up an asteroid so that all fragments are  $\leq 10$  m in size. This is obviously a higher energy density than that to just "break it in two," and we suggest should be of the order of the energy density needed to "break in two" a 10 m object,  $\sim 10^7$  ergs/gm.

Because of the large energy requirements to fracture a well consolidated asteroid, only nuclear explosives are considered. In order to relate the energy density as a function of radius for a completely coupled (buried) nuclear charge, we employ the empirical relations of shock-induced particle velocity,  $v$ , versus energy scaled radius ( $r/kT^{1/3}$ ) of Cooper<sup>16</sup>. For hard (mainly igneous) terrestrial rocks of Cooper finds

$$\ln_{10} v(\text{m/s}) = 5.233 - 2 \ln_{10} (r/kT^{1/3}) \quad (14)$$

where the  $r$ , radius is hydrodynamically scaled by the one-third power of explosive yield ( $kT^{1/3}$ ). Similarly, for soft rocks, Cooper finds

$$\ln_{10} v(\text{m/s}) = 4.590 - 2 \ln_{10} (r/kT^{1/3}) \quad (15)$$

Since the shock wave energy per unit mass is equal to  $v^2$ , the quantity

$$E_{\text{frac}} = v^2(r, kT^{1/3}) \quad (16)$$

where  $v^2$  can be specified via Eq. (14) or (15) and  $E_{\text{frac}} = 10^3 \text{ J/kg} = 10^7 \text{ ergs/g}$ . Upon substituting Eq. (15) into Eq. (16) for 1 kT, we find  $r = 35 \text{ m}$ . Thus, a 1 kT explosive is expected to fragment a 35 m radius sphere of rock, if the explosive is placed well within the asteroid. Also, a 1 megaton charge of explosive will fragment 350 m radii of rock and 1 Gton of explosive will fragment 3.5 km of rock. In contrast, for hard rock (Eq. 14), which describes less attenuative rock, gives the radius of fracture of 74 m for 1 Kton explosion. From Eq. 15, to deliver  $10^7 \text{ ergs/g}$  to 0.1, 1, and 10 km diameter asteroids requires 3 kT, 3 Mtons, and 3 Gtons, centrally placed.

The above discussion is based on the premise that the charge is buried to sufficient depth so as to obtain optimum fragmentation. There is good reason for desiring some nuclear charge burial, as surface exploded nuclear charges couple only a small fraction of their energy to rock (0.2 to 1.8%) for radiative and hydrodynamic coupling <sup>22</sup>, whereas the large fraction of the energy of a deeply buried charge is coupled into rock.

Figure 3 shows the charge depth for different  $d/a$  values and yield required to completely excavate asteroids of 100, 1,000, and 10,000 m diameter. The yield values required for an excavating charge are less by a factor of  $3 \times 10^3$  to 4 in going from 0.1 to a 10 km asteroid, than those calculated for fragmentation. These charges are in the 0.15 to 3 kton range for 100 m asteroid, 0.007-3 Mton for a 1 km asteroid, and 0.3 to 3 Gton for a 10 km diameter asteroid. The effect of gravity on the radius of excavated volumes is seen to be substantial. Notably, the optimum (largest radius of excavated volume) depth of charge decreases with increasing asteroid size and surface gravity. Fig. 3 also shows the radius of excavated volumes between craters on the Earth and a 10 km asteroidal object differ by a factor of up to 5 in going from the gravity of a 10 km diameter object,  $0.3 \text{ cm/sec}^2$  to that of the Earth ( $982 \text{ cm/sec}^2$ ). Dispersal seems to require about the same

energy as deflection, and also is benefitted by charge burial. Hence, asteroid deflection rather than destruction, via fragmentation, appears the favorable choice.

## CONCLUSIONS

We have examined the velocity criteria for perturbation of the orbits of earth-crossing objects (asteroids and comets) so as to cause objects which have trajectories which intersect the Earth to be deflected. For objects discovered only as they approach on a collision course, the velocity perturbations required are tens to hundreds of m/sec. Energy levels are prohibitive for larger bodies, and the required perturbation impulse would disrupt the body.

We also note that perturbation of an object perpendicular to its orbit is more effective by applying a change in velocity, ( $\Delta v$ ) along its original orbit and thereby inducing a change in orbital period, and hence the radius of the orbital axes. Upon applying an impulse at perihelion, gives rise to a  $\Delta v$ , which, in turn, provides a larger deflection  $\delta$ , after time,  $t$ , of the order of  $3\Delta vt$ , than can be achieved for perpendicular deflection.

For a ~100 m diameter asteroid, the kinetic energy of  $10^2$  to  $10^3$  kg impactors, intercepting at 12 km/sec will provide enough energy to crater and launch ejecta in the low gravity environment of these objects to induce velocity perturbations of in the order of 1 cm/sec. For larger diameter asteroids, deflection via this method appears impractical because of the large mass of impactors required. Mass drivers require launching  $\sim 10^3$  to  $10^4$  tons of asteroidal material to deflect from the Earth impact a 1 km asteroid over an interval of 30 years prior to encounter. Nuclear explosive irradiation may be used to blow-off a 20 cm shell encompassing ( $\sim 0.3$  times) the asteroid surface area by exploding a charge at an optimum height of  $h/R = \sqrt{2} - 1$ . Minimum charges of 0.01,  $10^2$ , and  $10^4$  Kton of explosives are required to cause this shell to blow-off and perturb the velocity of 0.1, 1, and 10 km asteroids by 1 cm/sec. However, less radiatively efficient explosives

may require an order of magnitude more explosive yields. Surface charges of  $10^{-2}$ , 10, and  $10^5$  Kton may be used to eject crater material to greater than local escape velocity, and hence, perturb 0.1, 1, and 10 km diameter asteroids by a velocity increment of  $\sim 1$  cm/sec. Burial of nuclear charges to induce fragmentation and dispersal requires in-situ drilling which is difficult on a low gravity object or technically challenging if dynamic penetration methods are to be employed. Optimally buried cratering charges required to completely excavate (working only against local gravity) 0.1, 1, and 10 km diameter asteroids require energies of  $\sim 1$  ton, 30 Kton and 0.8 Gtons, respectively.

Upon examining the deflection or fragmentation options, deflection appears to be the most promising goal because charge burial is not required or desirable. For a small (100 m) asteroid, the kinetic energy impact deflection method is both technically feasible and does not involve the politically complex issue of placing nuclear explosives on a spacecraft. For the 1 to 10 km range asteroids which includes the largest earth-crossing objects, only the nuclear option is practical. For this task, deflection via nuclear explosive radiation appears to be the simplest method. This would appear to require less detailed knowledge of the physical characteristics of an earth-crossing object, and the development of the charges required to deflect large earth crossing objects appear to be technically feasible.

Finally, we should note that while further study of the feasibility of diverting an asteroid may be warranted, we do not believe it is appropriate to conduct engineering designs of systems because:

1) low earth impact probability of hazardous asteroids; 2) high cost compared to low probability; 3) rapid changes in defense systems technology.

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## FIGURE CAPTIONS

Figure 1. Sketch of the use of nuclear explosive radiation to induce a ( $\sim 1$  cm/sec) velocity perturbation in a near earth asteroid. (a) Nuclear explosive designed to provide a substantial fraction,  $e$ , of its yield as energetic neutrons and gamma rays is detonated at an optimum height,  $(\sqrt{2} - 1) R$ , above an asteroid. At this elevation asteroid subtends 0.27 of the area of a unit sphere around the explosive and explosive irradiates 0.296 of the asteroid surface area (b) Irradiated to a depth of  $\sim 20$  cm, surface material subsequently expands and spalls away from the asteroid, inducing a several kilobar stress wave in the asteroid. (c) Blow-off of the irradiated shell induces a cm/sec velocity perturbation in the asteroid.

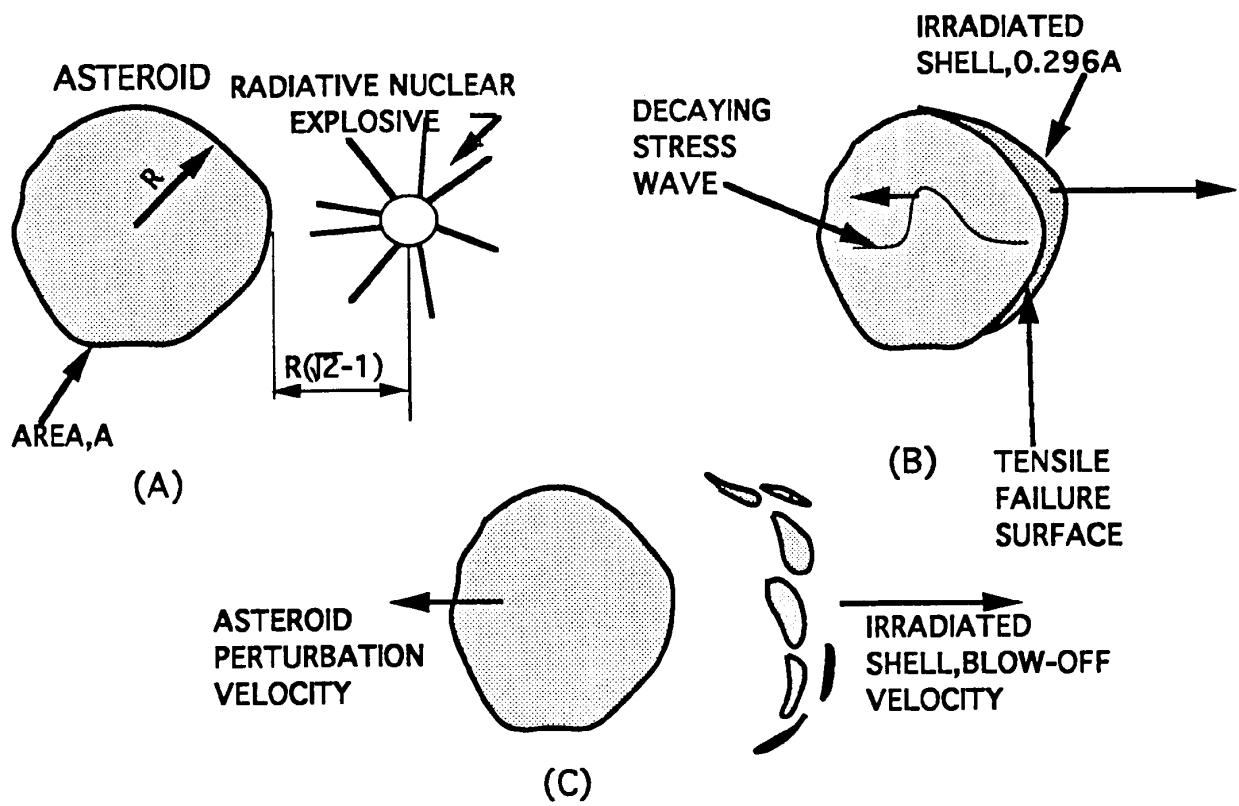
Figure 2. Mass ejecta accelerated to greater than escape velocity (left) for cratering explosive charges on surface and 0.1, 1, and 10 km diameter asteroid as a function of explosive yield. Plotted on right is the resultant asteroid velocity change resulting from momentum conservation. G, indicates gravity scaling and S, strength scaling of crater size and dynamics. The curvature of the velocity curve for strength scaling for a 0.1 km diameter asteroid, arises from the substantial fraction of the asteroid ejected by an explosive crater in the 30 bar strength material.

Figure 3. Radius of excavated sphere of asteroidal material for 0.1, 1, and 10 km asteroids, versus, normalized charge depth. Effect of nominal yield explosive for each size asteroid indicated. The effect of gravity is demonstrated by the curve labeled "Earth Gravity" which gives the excavated crater volume assuming terrestrial rather than asteroidal gravity for the 10 km asteroidal case, where a 0.83 Gton explosive charge yields a radius of excavated volume of crater of 5 and 1 km on the asteroid and Earth, respectively.

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Asteroid Velocity Change (cm/sec)

